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Abstract. Hydrodynamic growth and its effects on implosion performance and mix were studied at the National Ignition Facility (NIF). Spherical shells with pre-imposed 2D modulations were used to measure Rayleigh-Taylor (RT) instability growth in the acceleration phase of implosions using in-flight x-ray radiography. In addition, implosion performance and mix have been studied at peak compression using plastic shells filled with tritium gas and imbedding localized CD diagnostic layer in various locations in the ablator. Neutron yield and ion temperature of the DT fusion reactions were used as a measure of shell-gas mix, while neutron yield of the TT fusion reaction was used as a measure of implosion performance. The results have indicated that the low-mode hydrodynamic instabilities due to surface roughness were the primary culprits to yield degradation, with atomic ablator-gas mix playing a secondary role.

1 Introduction

Hydrodynamic instabilities and mix play a central role in the performance degradation; any drive asymmetries and surface imperfections are amplified by the hydrodynamic instabilities during implosion resulting in a distorted shell with reduced hot-spot temperature, volume, and pressure [1]. In addition, small-scale turbulence seeded by these instabilities can mix ablator material into the DT hot spot [1]. The presence of mixed ablator material was correlated with reduced experimental yields and temperatures in high-compression layered DT implosions [2], but it has not been directly measured. Layered DT implosions have previously been modeled using 2D simulations intended to capture performance degradation due to instabilities and drive asymmetries [3], but lacking a model to predict atomic ablator-fuel mix [4]. These simulations over-predicted the yields by a factors from ~5 to ~30 for high-compression implosions. As a way to explain the measured performance, 2D simulations used large, un-physical multipliers (up to 3-5x) on the capsule surface roughness to bring simulated yields down to the measured levels [3]. This prompted a hypothesis that the instability growth factors were larger than in 2D simulations. Since the discrepancies were especially pronounced in implosions with significant inferred ablator-fuel mix [2], it also suggested another hypothesis that atomic mix was a major contributor to yield degradation because there were no models of atomic mix used in 2D simulations.

Two sets of experiments were designed to test hypotheses about lower growth factors used in simulations, and the atomic mix being the dominant factor in performance degradation.

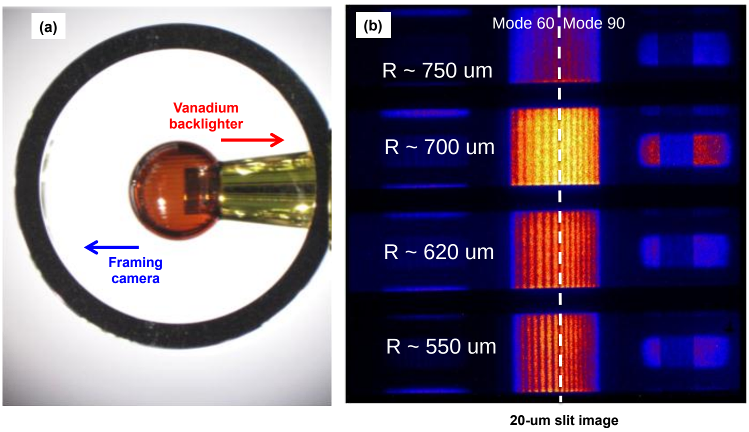

Fig. 1. (a) Image of the capsule and the gold cone. (b) Measured capsule radiographs captured on a framing camera. The central four images of the growing capsule modulations were formed using 20-μm wide slit at shell radii of 750 μm, 700 μm, 620 μm, and 550 μm. The capsule had pre-imposed, side-by-side, 2D sinusoidal modulations at mode numbers of 60 and 90.

The ablation-front RT instability experiments are described in Sec. 2; while the atomic-mix experiments near peak compression are discussed in Sec. 3. The results are summarised in Sec. 4.

2 Ablation-front Rayleigh-Taylor instability experiments

Rayleigh-Taylor growth experiments were designed to measure instability growth factors at the acceleration phase of spherical implosions at National Ignition Facility [5]. Figure 1(a) shows an image of the capsule and the gold cone used in these experiments. The capsules had pre-imposed, 2D sinusoidal modulations at three wavelengths, 240 μm (mode 30), 120 μm (mode 60), and 80 μm (mode 90). The initial modulation amplitudes were in the range from 0.4 μm to 1.7 μm. The gold cone provided a possibility for the backlighter x-rays to pass through a single wall of the shell, enabling high-quality radiographs of the growing modulations. The experiments were conducted with shaped, ignition-like pulses, with total laser energies of ~1.3 MJ and peak x-ray radiation temperatures of ~280 eV. The pulses were the energy-scaled version of the drive used in layered cryogenic DT implosions. The nominal 209-μm thick plastic capsules with nominal 1120-μm outer diameters had the same Si-doped layers, as used in other similar implosions experiments. Figure 1(b) shows measured capsule x-ray radiographs captured on a framing camera. The central four images of growing capsule modulations were formed using 20-μm wide slit, while images on right and left sides of the slit images were formed with 20-μm and 50-μm pinholes. The temporal resolution of the framing camera was 100 ps, while spatial resolution of the slit images was 20 μm. The images were formed using ~5.4 keV x-rays generated by a vanadium backlighter. The measurements were conducted for convergence ratios up to ~2, when the shell radius was decreased down to ~500 μm in the implosions.

Figure 2 shows measured optical-depth growth factors for the modes 30, 60, and 90 as a function of mode number. The results are compared with simulation predictions at shell radius of 620 μm. While the measured growth factor at mode 30 was close to that predicted, the measured growth factors at modes 60 and 90 were larger than predicted by factors of ~1.3 and ~2.5, respectively. These results demonstrated that ablation-front growth factors were under-predicted in the simulations used to model the performance of layered DT implosions. They also indicate that lower predicted growth factors used in 2D simulations can partially explain the need for large, un-physical multipliers on the capsule surface roughness to bring simulated yields down to the measured levels.

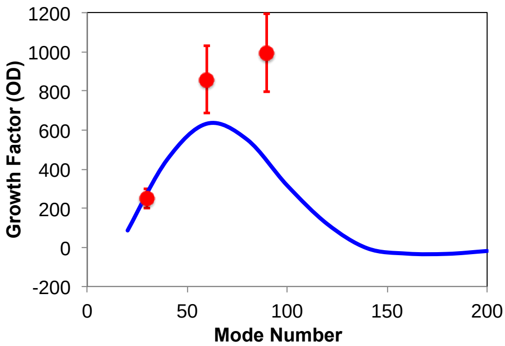

Fig. 2. Measured (circles) and simulated (solid curve) optical-depth growth factors as a function of mode number at shell radius of ~620 μm.

3 Atomic-mix experiments in the deceleration phase

Figure 3(a) shows the capsule schematic and the laser pulse used in the atomic-mix spherical implosion experiments. Plastic shells had a nominal 209-μm thickness and 2280-μm-initial outer diameter. Si-doped layers were included to reduce preheat of the inner CH ablator from 2-4 keV M-band emission from the Au hohlraum wall. The capsules included a CD layer with 4.0-μm thickness, placed at either the inner shell surface, or offset by up to 8.0 μm from the inner surface by the CH-only layers. The shells were filled with tritium gas that included a small contamination of deuterium gas of 0.1% by atom fraction. All implosions used a laser pulse with peak power of ~435 TW and total laser energy of ~1.5 MJ.

In implosions without CD layers (labeled "CH capsules"), the measured TT and DT yields along with DT ion temperatures probed the conditions in the central part of the core. In implosions with CD layers, the TT yields were similar to those in the CH capsules, while DT yields were higher (up to ~6 times), and DT ion temperatures were lower (~ 2.0 keV vs 3.4 keV). The lower measured temperature supported the hypothesis that the DT neutrons were primarily generated in the colder region where D and T were atomically mixed. As the recession of the CD layers from the inner surface increased, the measured DT yields decreased, indicating that much of the plastic mixed into the gas came from a region close to the inner surface.

The experimental results were compared with 2D simulations using the code ARES [6]. To capture large wavelength low-mode (l <~ 100) instabilities, simulations were performed using an angular resolution of 1/8 degree, with imposed surface roughness at unstable interfaces. The K-L mix model [4] was included to capture the turbulent regime and the effects of mix at scales smaller than the computational grid. The free parameter in this method was the initial turbulent mixing length, L_0, set at all unstable interfaces.

As shown in Fig.3, the simulations match well the whole set of experiments. For this, a multiplier of 3 times on the nominal outer surface roughness was needed to match the measured conditions in the central hot core, as determined by the TT yield. The measured outer surface roughness in these experiments varied from 0.5 to almost 2 times the nominal value used in our simulations; thus the 3x nominal values needed to match the TT yield represent up to a factor of ~6 above the measured roughness. This need for a multiplier is consistent with previous 2D simulations of high-compression layered DT implosions [3]. To explain the conditions in outer colder core (DT yield and ion temperature), a low roughness parameter of L_0=0.1 nm was used in the K-L mix model. These results indicated that the low-mode hydrodynamic instabilities due to surface nonuniformities were the primary reason to yield degradation, with atomic ablator-gas mix playing a secondary role.

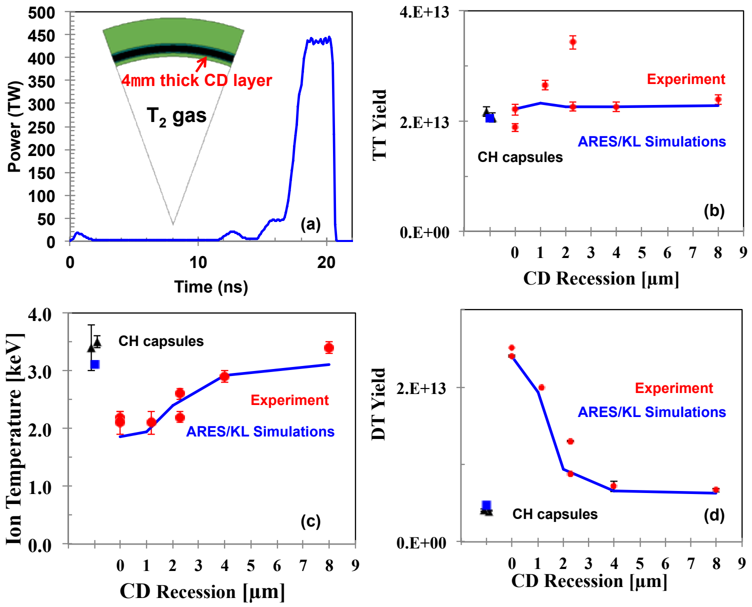

Fig. 3. (a) Pulse shape used in experiments. Schematic of the capsule with a 4-µm thick CD layer, placed either at inner shell surface, or recessed up to 8 µm form the inner surface by CH layers. Measured and simulated (b) TT neutron yield, (c) ion temperature, and (d) DT neutron yield, as a function of recession depth of the CD layer, and for CH capsules without CD layer. Results of 2D ARES simulations including K-L mix model are shown with solid curves. The squares represent simulations of the CH capsules without CD layers.

The implosion results were also consistent with higher measured growth factors at ablation front, compared to those predicted in simulations, as shown in the previous Section.

4 Conclusions

The results of ablation-front, Rayleigh-Taylor instability experiments have shown that modulation growth was under-predicted in 2D simulations at low mode numbers of 60 and 90, while it was close to predictions at the mode number of 30. The results of atomic-mix experiments using plastic shells with CD layers have indicated that the low-mode hydrodynamic instabilities due to surface roughness were the primary culprits to yield degradation, with atomic ablator-gas mix playing a secondary role.

5 Acknowledgements

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